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Iceberg scours, pits, and pockmarks in the North Falkland Basin

Christopher S. Brown [a,d,*], Andrew M.W. Newton [a,b], Mads Huuse [a,b], Francis Buckley [c]

[a] School of Earth and Environmental Sciences, University of Manchester, M13 9PL, UK
[b] Cryosphere Research at Manchester, University of Manchester, M13 9PL, UK
[c] Lloyd's Register Survey and Geoengineering Ltd., UK
[d] Department of Civil Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

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ABSTRACT

Glaciation in the Southern Hemisphere is limited by the availability of land from which to seed ice sheets. The extents of the Antarctic, Patagonian, and New Zealand Ice Sheets at the Last Glacial Maximum (LGM) are relatively well known, although the rates and styles of their retreat after the LGM are poorly constrained, particularly in Antarctica. Offshore records of glaciation are relatively sparse in the Southern Hemisphere despite the potential ocean-climate insights that can be gained from records of glaciation that are preserved offshore. In this study, we document the occurrence of iceberg scours and accompanying pits within the North Falkland Basin (c. 50° S) and discuss their origin. The cross-sectional shapes of scours are u- to v-shaped and occur in present-day water depths of 280 to 460 m. Individual scours are up to 38 km long, 1 km wide, and up to ~10 m deep. The scours are observed as erosional linear to curvilinear depressions, showing only one point of contact between the iceberg and seafloor, often with raised berms, composed of excavated material, identified either side of the main depression. Undulating width of scours is interpreted as an effect of rotation of the iceberg keel during scour excavation. The elongate morphology of the scours differentiates them from asymmetrical pits, interpreted to represent iceberg impact pits, and symmetrical pockmarks, interpreted to form due to fluid expulsion. In cross-section the differentiation is highly interpretative, but the 3D bathymetric expression is unequivocal. The sinusoidal character of the scours suggests the interaction between local tidal currents and the East Falkland/Malvinas Currents in the North Falkland Basin at the time of formation. Offshore and onshore landscape analysis is used to determine potential sources of icebergs and suggests that they were most likely sourced from the Antarctic Peninsula. These results inform our understanding of Southern Hemisphere ocean-climate interactions during the last glacial cycle and suggest that the East Falklands/Malvinas Current, a key current in the Southern Hemisphere bringing cold, low-salinity Antarctic-derived waters into the South Atlantic, was in operation during the last glacial cycle. The accumulation of icebergs west of the Falkland Islands would also result in further cooling from fresh, meltwater perturbations, enhancing the development of a potential ice-bridge along the Argentinian coast.

1. Introduction

Iceberg scours are a common feature on many high-latitude margins and are formed when a floating iceberg becomes partially- or fully-grounded on the seafloor. Subsequent ocean currents, tidal changes, storms, subglacial drainage, and calving events can then drive the iceberg forward, scouring the seafloor, leaving a record of its trajectory behind (Bass and Lever, 1989; Woodworth-Lynas, 1996; Carlson et al., 2005; Goff and Austin, 2009; Newton et al., 2016). When iceberg scouring events occur, they provide insight into oceanic and glaciological conditions that can be indicative of past climate-ocean interactions on a range of spatial scales (Todd et al., 1988; Dowdeswell and Bamber, 2007; Newton et al., 2016). Their preservation within the geological record is thus significant for palaeo-environmental reconstructions from local to hemispheric scales.

In the Northern Hemisphere, a large number of studies have documented the occurrence of iceberg scours across multiple glaciated margins (Barnes and Lien, 1988; Syvitski et al., 2001; Goff and Austin, 2009; Sacchetti et al., 2012; Batchelor et al., 2013). Iceberg scours have also been found buried at several levels within the Pleistocene (Goff and Austin, 2009; Buckley, 2012, 2014; Dowdeswell and Ottesen, 2013), whilst some scour marks have been identified great distances from their prospective sources, reaching low- to mid-latitudes along the

* Corresponding author at: Department of Civil Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK.
E-mail address: CSB600@student.bham.ac.uk (C.S. Brown).

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Southern US Atlantic margin (Duncan and Goff, 2001; Hill et al., 2008; Hill and Condron, 2014). In the Southern Hemisphere, comparatively few iceberg scour studies have been documented outside of Antarctica, with even fewer being documented at mid-latitudes (López-Martínez et al., 2011). At present, icebergs have rarely been recorded north of the Falkland Islands, with only giant icebergs capable of reaching warmer waters (Silva et al., 2006). In this paper, we document iceberg scour morphology, location, and potential sources for icebergs affecting the North Falkland Basin (NFB). The landform record is finally used to inform the palaeo-oceanography of the South Atlantic during the last glacial cycle.

Pockmarks and iceberg pits are circular features that share similar characteristics and are recorded around the world. Pockmarks are circular to elongate crater-like depressions that have been found in a range of marine settings, generally ranging from 10 to 250 m diameter (Pilcher and Argent, 2007). Pockmarks are related to fluid flow and form when fluid is expelled from the seabed in fine-grained sediment (Hovland and Judd, 1988; Dando et al., 1991). Iceberg pits are observed as circular to semi-circular depressions, created when an iceberg re-adjusts its hydrostatic equilibrium when melting, impacting the sea floor (Syvitski et al., 1996, 2001), or through the temporary grounding of an iceberg during low tidal conditions. Pits and pockmarks are distinguished on the basis of morphology, stratal relations and the association, or not, with subsurface fluid flow indicators (e.g. Cartwright et al., 2007; Løseth et al., 2009). In most cases this set of criteria allows the circular depressions to be related to either fluid flow or the movement of icebergs, but in some cases a clear distinction cannot be made on fully objective grounds.

2. Regional setting

The NFB is located on the Falkland Plateau, an extension to the Argentinian continental shelf, in water depths reaching up to 2500 m (Arhan et al., 2002), deepening northward and eastward (Fig. 1). The Falkland Islands represent a small proportion of the Falkland microplate (Mitchell et al., 1986). The earliest glacial sediment encountered on the Falkland Islands was deposited in the Carboniferous, when Gondwana was situated in southern polar latitudes and covered by ice sheets, with tillites and erratic boulders found (Stone, 2010). The NFB developed in the late Jurassic to early Cretaceous, during the disintegration of Pangea and extension of the South Atlantic, leading to lacustrine-fluvial conditions and the more recent marine setting (Richards and Hillier, 2000). Recently, during the Pleistocene, low sedimentation rates have been recorded on the Falkland Plateau (Barker et al., 1977), and along the Argentinian shelf (López-Martínez et al., 2011). It is therefore assumed in this study that sediment accumulation has been low throughout the Pleistocene.

Ocean currents in the South Atlantic are a crucial component of the global thermohaline circulation. In addition to the North Atlantic, deep-water production is also found in the Weddell and Ross Seas off of Antarctica. In the western side of the South Atlantic, deep- and bottom-water flows between the North Atlantic and the Antarctic Circumpolar Current (ACC) result in large fluxes of heat between different latitudes and the different hemispheres (Rahmstorf, 2002). The ACC is a major current in the South Atlantic, due to its high influence in sub-Antarctic waters (Fig. 1). It is an eastward-flowing current, connecting all of the Earth's major oceans and is driven by westerly winds at latitudes of 45°–55° S (Trenberth et al., 1990; Orsi et al., 1995). The ACC circulates the Antarctic Peninsula and represents an important region of transition between Antarctic and sub-Antarctic waters (Meinardus, 1923; Nowlin and Klinck, 1986).

3. Data and methods

Five high-quality 3D seismic datasets, covering an area of 1550 km^2 (Fig. 1) were used, focusing on a geomorphological analysis of the seafloor and the shallow subsurface, in water depths of 300–500 m. The 3D datasets were acquired during an exploration campaign between 2010 and 2011, by Desire Petroleum and Rockhopper Exploration (MacAulay, 2015; Subsea IQ, 2017). The Polarcus Nadia; a 12 streamer 3D seismic vessel, that uses dual sources and a multi-streamer Sercel Seal Marine Data Acquisition system, was used to obtain the data (Polarcus, 2017; Subsea IQ, 2017). In the near seabed sediment, using a velocity of 1800 m/s, the 3D seismic data have a frequency of 30 to 50 Hz, a vertical resolution of ~15 to 9 m and horizontal resolution of 30 to 18 m respectively. Supplementary 2D seismic lines were also used, which cover several different parts of the margin (Fig. 1b). This is legacy data with a typical resolution of ~20 to 40 m and is provided through the British Geological Survey and the Falkland Islands' Department of Mineral Resources.

Data were analysed using Petrel software, ArcGIS, and Microsoft Excel. Curvilinear and sinuous features interpreted as iceberg scours, and pitted features interpreted as pockmarks and iceberg pits, were identified on the seafloor using surface attributes such as depth, amplitude, dip and dip-azimuth, and a variable light source in order to highlight the more subtle morphologies on the gridded surfaces. These features were then digitised and exported to ArcMap where their geometries were analysed. In order to consider prospective source locations for the icebergs, satellite imagery and topographical analysis in Google Earth were used in combination with published literature to assess the most likely location of the parent ice sheet.

We infer that the freshness and lack of reworking of the scours suggests that they are a relatively recent formation and that they probably formed during the Last Glacial Maximum (LGM) and the ensuing deglaciation, when large ice sheets were available to seed deep-keeled icebergs in such quantity. However, given the low sedimentation rates, it is possible that some scours are relicts from prior glaciations.

4. Characterisation of seabed erosion features and their origin

All the seabed depressions found in this study share a cross-sectional morphology ranging from u- to v-shaped. Iceberg scours are easily distinguished based on 3D seismic or multibeam bathymetry and sidescan data or 3D seismic timeslices due to their curvilinear to sinusoidal planform, whereas iceberg pits and pockmarks are more difficult to distinguish, given both are largely circular in plan view. Though pockmarks and iceberg pits have a similar morphology, they form through different means; pockmarks are related to fluid expulsion, whilst pits are related to the movement of icebergs in the water column. The depressions can be distinguished by their relationship (or not) with fluid-flow indicators, location, stratigraphic and palaeo-environmental context, symmetry, diameter, and seismic distortion. These characteristics are mostly not unequivocal so the full suite of characteristics is used to distinguish the two types of features and even then may result in an ambiguous partitioning.

Iceberg pits are only found in sediment exposed during glacial or post glacial conditions, forming when icebergs periodically impact the seafloor due to instabilities caused by buoyancy or changes in water depth. In this study, iceberg pits are generally found on the seafloor or just below it. Pitted features are usually concentrated in proximity to iceberg scours, due to instabilities created by buoyancy (Dowdeswell et al., 1993; Syvitski et al., 2001). Pits can also be identified in linear arrays, typically referred to as crater- chains, forming as an iceberg repeatedly hits the seafloor (Bass and Woodworth-Lynas, 1988). Iceberg pits are often surrounded by a berm consisting of ejected material (Fader et al., 1988; Mortensen and Buhl-Mortensen, 2004). As an iceberg becomes grounded, sediment is excavated in an upward and outward motion caused by the iceberg keel ploughing the seafloor (Eden and Eyles, 2001; Van Landeghem et al., 2009). Sediment is then deposited on the far side of the pit as a berm or rim, causing asymmetry. Pits can vary in diameter and have been found ranging in diameter between 10 and 700 m (Geirsdóttir et al., 2008; McKenzie et al., 2013). They are usually

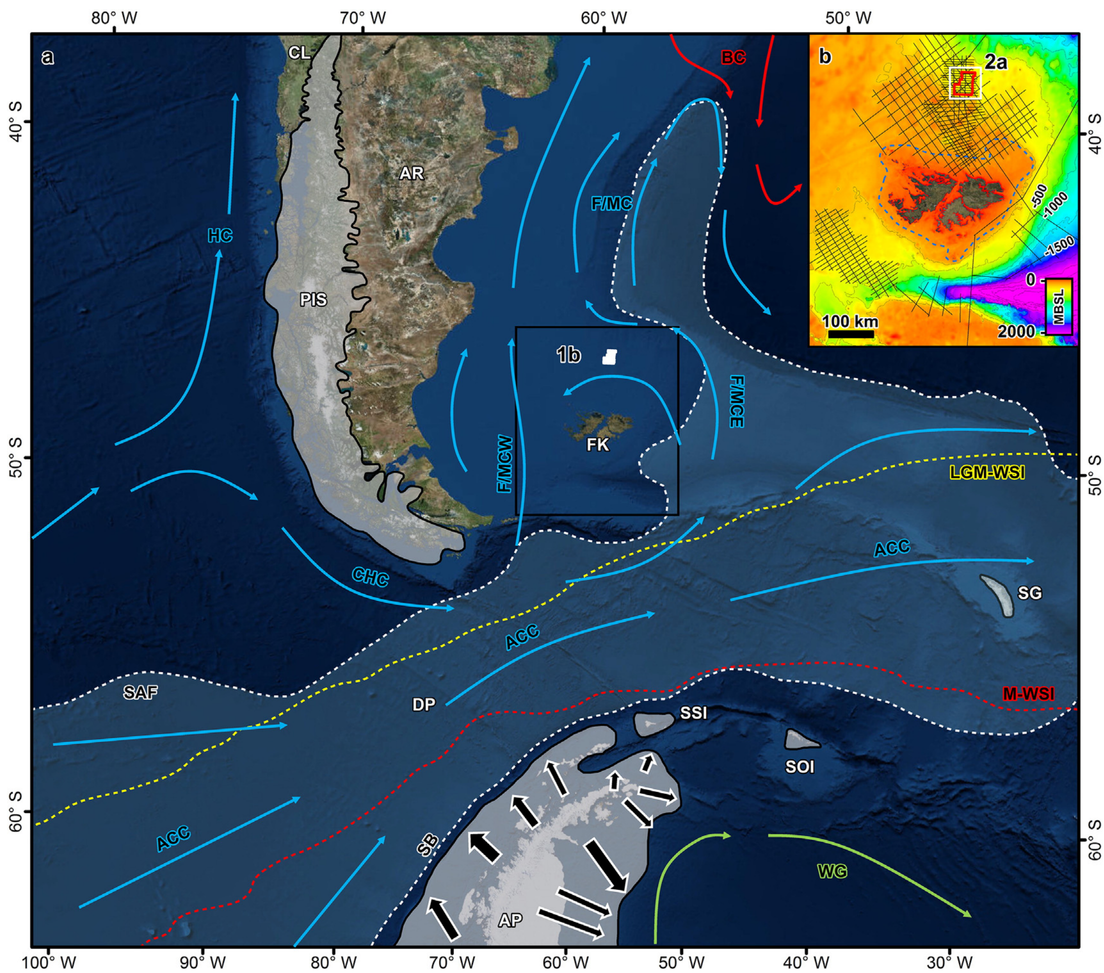

Fig. 1. (a) study site map showing the distribution of the Patagonian Ice Sheet (PIS), the Antarctic Peninsula (AP), and the sub-Antarctic islands at the LGM (Graham et al., 2008; Kaplan et al., 2009; Davies et al., 2012; Dickens et al., 2014; Hodgson et al., 2014). Ice streams over the Antarctic Peninsula are indicated with black/white arrows, where thickness is proportional to size. The LGM winter sea ice extent is shown (LGM-WSI) and the present (M-WSI) (Gersonde et al., 2005). Across several of the sub-Antarctic islands, the full extent of the ice cover during the last glacial is poorly resolved. As such, in our reconstruction we provide a conservative estimate of ice cover over the sub-Antarctic islands that is more proximal to the coast than the shelf edge. Much of the information on the offshore extent of the ice sheets should be considered tentative as only limited information is available. The contemporary Antarctic Circumpolar Current (ACC) is shown in the transparent grey polygon overlying the ocean. ACC boundaries are marked with dashed white lines indicating the Sub-Antarctic Front (SAF) and the Southern Boundary (SB). The blue and red arrows show the circulation patterns of the upper ocean layer around South America and the Antarctic Peninsula. The blue arrows indicated cooler ocean currents originating from Antarctica and the ACC, whilst the red arrows indicate warmer, sub-tropical flow from lower latitudes. Abbreviations for the ocean currents are as follows: Humboldt Current (HC), Cape Horn Current (CHC), Falklands/Malvinas Current Western branch (F/MCW), Falklands/Malvinas Current eastern branch (F/MCE), Falklands/Malvinas Current (F/MC), and the Brazil Current (BC). The green arrows show the Weddell Sea Gyre (WG). Oceanographic information has been compiled from Orsi et al. (1995); Piola and Matano (2001); Kaiser et al. (2005); Carter et al. (2008); Matano et al. (2010). Additional abbreviations include: Drake Passage (DP), Antarctic Peninsula (AP), South Orkney Islands (SOI), South Shetland Islands (SSI), South Georgia (SG), Argentina (AR), Chile (CL), and the Falkland Islands (FK). Base satellite imagery map is from the World Imagery Layer available from ArcMap Online. (b) Shows the location of the study site in the North Falkland Basin. Bathymetry is from GEBCO and the satellite imagery is from the World Imagery Layer from ArcMap Online. Red polygon shows the outline of the 3D seismic data used here. The thin black lines show the distribution of 2D seismic reflection data. The location of this panel is shown in (a), whilst the location of Fig. 2a is also indicated by the white box. Contours are measured every 250 m. The blue dashed line marks the 134 m contour bathymetric contour and provides a rough estimate of sea level at the LGM (Lambeck et al., 2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

not associated with seismic distortion through dimming or elongate pipe-like structures.

Pockmarks can be identified on seismic data as circular to elongate depressions, representing erosive craters caused by sediment blow out associated with focused fluid flow at the seabed (Cartwright et al., 2007). Pockmarks are mostly circular, but elongate pockmarks occur where they have been modified by bottom current scours (e.g. Andresen et al., 2008). In this study, the observed pockmarks are symmetrical and round, suggesting low-to-moderate bottom current speeds. Diameter can vary between 100 and 1000 m, with a global average of 128 m taken from 57 studies (Pilcher and Argent, 2007). On seismic reflection images, pockmarks truncate underlying reflections and are often associated with an acoustic dimming (Cartwright et al., 2007) and sub-vertical, discontinuous pipe-like signatures beneath the seafloor. Seismic reflections directly below a pockmark can be pulled up into a series of local anticlines, with vertical changes in polarity (Løseth et al., 2001) or amplitude anomalies related to gas (Cartwright et al., 2007). Multiple stacked pockmarks can also be identified on seismic data as a series of local, vertically-layered depressions. Stacked pockmarks occur when pockmark development is repeated over the same location through a sustained period of deposition (Çifçi et al., 2003; Andresen and Huuse, 2011). Another characteristic used to distinguish pockmarks and pits is the presence (or not) of a berm, adjacent to the feature. Pockmarks typically do not have berms or ejecta rims, which are often associated with iceberg pits. This is because pockmarks form from fluid expulsion in fine-grained sediment, which is then removed in suspension by ocean swell and other seafloor currents (Webb, 2009).

Distinguishing between the circular pitted features requires both morphometry and associated observations, such as seismic distortion or pitted features proximal to scours, to develop a high level of confidence. In the study area, it is also possible to ascertain confidence when identifying the type of pitted feature based upon the location below the seabed. Only the upper 50 m of seismic data below the seafloor retains a record of sediment incised by icebergs since the LGM, whereas below this (up to ~300 m below the seafloor) shows no evidence of submarine landforms caused by icebergs. It is therefore possible to conclude with some confidence that the pitted features from 50 to 300 m below the seafloor are pockmarks caused by fluid escape.

The confidence when interpreting the pitted landforms on the seabed is reduced, due to the reworking of sediment and overprinting of other pits or scours. To determine the nature of the feature, i.e. pockmark or pit, all characteristics are used to make the best distinction possible (Table 1). Even then, the nature of the landform can be unclear. Limitations in seismic resolution can also prevent subtle differences in morphometry being identified. The majority of the pitted features on the seafloor are therefore interpreted as iceberg pits. It is, however, important to acknowledge the presence of pockmarks and the ambiguity in distinguishing the origin of the circular depressions.

5. Results

5.1. Iceberg scour morphology

A large number of depressions are found on the seafloor of the NFB (Figs. 2–6). The largest depressions form grooves on the seabed that vary between being irregular and discontinuous to regular and continuous (Fig. 2a). There are linear to curvilinear depressions, with the majority of the features showing an undulating geometry, some with abrupt changes of direction. These features are interpreted as iceberg scour marks that formed when the draft of an iceberg exceeded water depth and ran aground dragging its keel, leaving a trajectory behind, recording the effects of wind and ocean current drag (Woodworth-Lynas et al., 1984; Hill, 2016; Newton et al., 2016; Stewart et al., 2016). The scours typically measure 50–400 m in width and 100s of metres to 10s of km in length (with a maximum width and length of 1 km and 38 km respectively), and up to ~10 m deep (Figs. 2–3). Scours are identified in water depths up to ~460 m below sea level. Assuming a sea level drop of ~130 m at the LGM (Lambeck et al., 2014), icebergs would have been scouring in water depths of up to ~330 m. The linear depressions are u- to v- shaped (Fig. 2) and, although not always present, raised berms, a few m high, ~50 m wide, can be identified either side of the main depression on seismic data (Fig. 3).

Undulating scour width and depth can be observed in some cases, particularly for longer scours; this is interpreted to be caused by rotation of the iceberg keel during scour formation (Dowdeswell and Ottesen, 2013). The scours appear unrelated and irregular in distribution as they crosscut each other throughout the study area. 587 scours were identified and an analysis of the iceberg scour orientation shows a bi-directional trajectory (Fig. 2b). The main trends are NE-SW and SE-NW, suggesting a broad E-W or W-E trajectory of the icebergs as they scoured. 'C' shaped features are identified on the seafloor in the northern part of the study area (Fig. 2a). These are interpreted as being formed by icebergs moving in an arcuate trajectory roughly parallel to the coast (Fig. 2). The iceberg would have moved toward the coast of the Falkland Islands, becoming grounded as it moved into shallower water, before a gradual rotation of trajectory by 180° and retreat into deeper water, resulting in the iceberg eventually becoming afloat. The arcuate trajectory and movement to and from the coastline is indicative of tidal forcing (Newton et al., 2016).

Table 1
Summary of characteristics used to identify the nature of pitted features in the North Falkland Basin. Note depths are given in metres below the seafloor (BSF).

Diagnostic	Pockmark	Iceberg pit
Location	0–300 m BSF	0–50 m BSF
Berm	No berm present	Berm present
Associated features	Distorted seismic below	Crater-chain/scours
Symmetry	Symmetrical	Asymmetrical
Diameter	100–1000 m	10–700 m
Shape	Conical	Irregular - angular to conical
Stacking	Singular or stacked	Singular

5.2. Iceberg pits and pockmarks

562 circular to sub-circular depressions were imaged on the seafloor (Figs. 6 and 7). These could have been caused either by the temporary grounding of an iceberg through tidally-influenced changes in sea level (pits), or by expulsion of fluid through the seafloor (pockmarks) (Fig. 8). A series of pitted features interconnected in a line were identified (Fig. 2f). We interpret these as a crater-chain, resulting from repeated iceberg impacts on the seafloor (Bass and Woodworth-Lynas, 1988). As the iceberg was partially grounded, it would have been driven forward by the ocean swell forcing the iceberg to oscillate vertically up and down, leaving a record of connected or semi-connected pits (Bass and Woodworth-Lynas, 1988; Newton et al., 2016).

Distinguishing between iceberg pits and pockmarks outside the crater-chains can be achieved by investigating morphometry and seismic data below the seafloor (as discussed in Section 4). Pockmarks are identified on the seismic data as circular to oval shaped depressions, sometimes, but not always, overlying a columnar zone of disturbed seismic reflections with local amplitude anomalies (Figs. 4 and 7a, b and g) (Cartwright et al., 2007). It is difficult to differentiate iceberg pits from pockmarks on the seabed, because the seabed is heavily scoured and has been subjected to low sedimentation rates since the Pleistocene (Barker et al., 1977). Circular depressions on the seafloor range between 100 m and 1 km in diameter. They are distributed across the entire area, usually in proximity to scour marks (Figs. 6 and 7).

Pockmarks and pipe-like features are also identified in the subsurface. Pockmarks in the subsurface are interpreted as palaeo-pockmarks, which formed when the seismic horizon was the seabed (Fig. 7i and j). They are only briefly described here as the study's primary focus is on submarine landforms created by icebergs. Pockmarks in the subsurface are particularly prominent on unconformities between different seismic facies through the Cenozoic (Fig. 4). The largest pockmark observed is ~1 km in diameter and is part of a stacked pockmark succession located in the west of the area (Fig. 7j). There is a relatively low quantity of stacked pockmarks observed across the dataset, compared to single pockmarks. Single pockmarks are only seen in the top 300 m below the seabed and range from 250 to 700 m in diameter. Pockmarks are not always associated with underlying pipes and are larger than the global average (128 m diameter; Pilcher and Argent, 2007).

Pipes vary considerably in size and depth below the seabed. The main trend is widening of the pipes upwards. In seismic data (Fig. 7), two types of pipes are identified: shallow (Fig. 7a–c) and deep rooted (Fig. 7j). The shallow pipes are within 100 ms (~100 m) of the seafloor and are seen on seismic data as a dimming and vertical discontinuation of reflections. Deeper, vertically-elongated pipes tend to be connected to larger diameter pockmarks. Deeper pipes also show evidence of pockmark stacking – suggesting continuous fluid supply over geological time (Fig. 7j). The deepest roots seen are visible to 310 ms (~300 m) with high confidence. Potential roots are seen as deep as 725 ms (~700 m) below the seabed.

6. Discussion

6.1. Identifying sources of icebergs and subsequent glacial implications

Detailed stratigraphic time constraints are not available for the area, the seismic record indicates little sedimentation has occurred since iceberg scour and pit formation. Consequently, the LGM (~21 ka), de- and post glacial period is considered the most reasonable time frame for

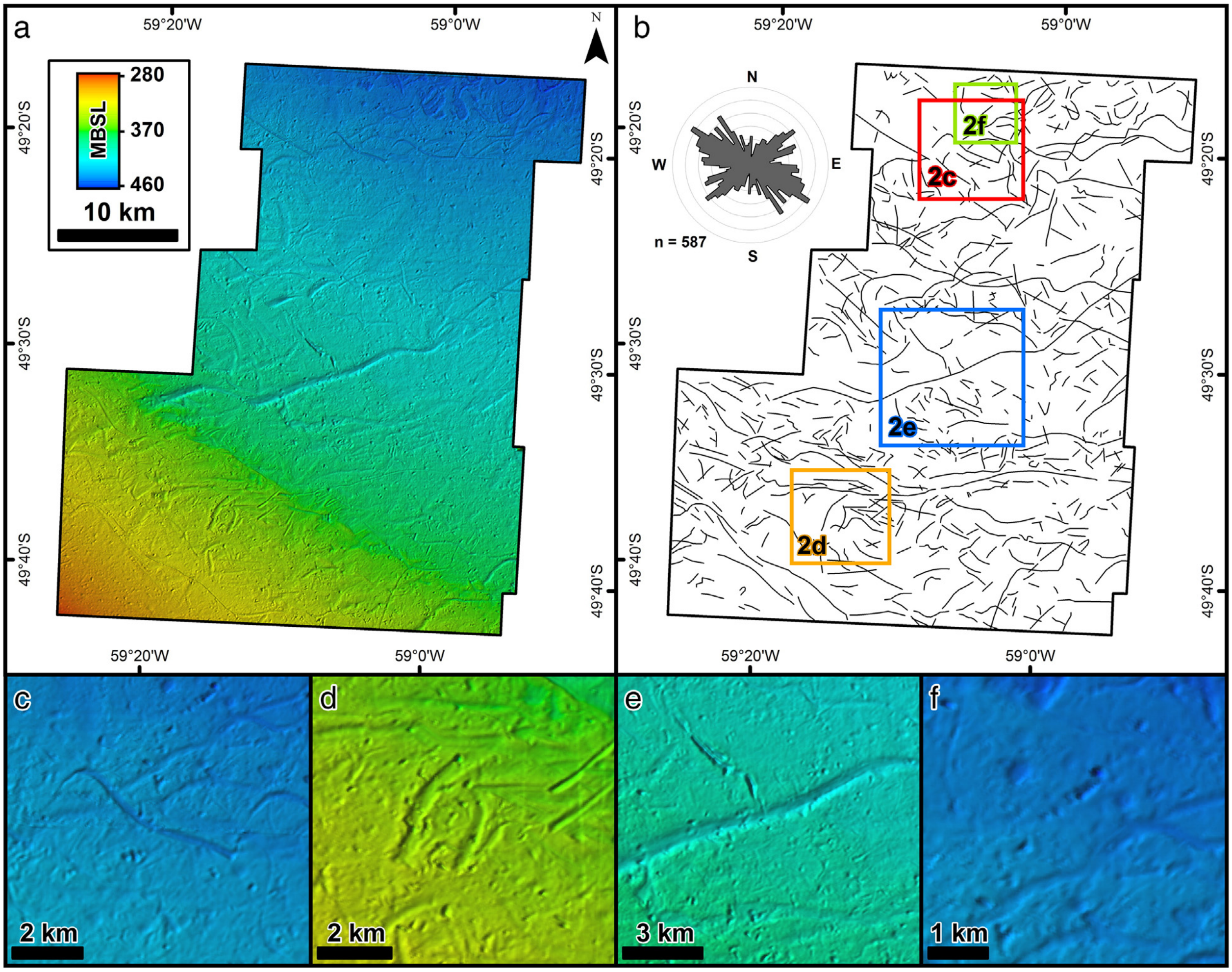

Fig. 2. (a) Bathymetric survey showing the iceberg scours cutting the seafloor. For location see Fig. 1. (b) Digitised iceberg scours observed on the seafloor. These were digitised using a range of lighting conditions to help highlight the more subtle scours. The locations of panels (c)–(f) are indicated. (c) Example of a sinusoidal iceberg scour formed as an iceberg was moved by local tidal currents and the East Falkland/Malvinas Current. (d) Example of iceberg scour surrounded by multiple pitted features. (e) The largest iceberg scour observed across the survey measuring up to 10 m in depth and ~38 km in length. (f) A set of pitted features that appear to be connected in a line. This has been interpreted as a crater-chain iceberg scour formed by an iceberg oscillating in response to the passing ocean swell.

iceberg scouring and four possible sources were identified for the icebergs (Huybrechts, 2002; López-Martínez et al., 2011). These sources include the Antarctic, Patagonian, and South Georgia Ice Sheets, as well as the potential for local sourcing from the Falkland Islands. Using a combination of Google Earth (2016) and published literature, these sources were assessed based on their present-day glacial

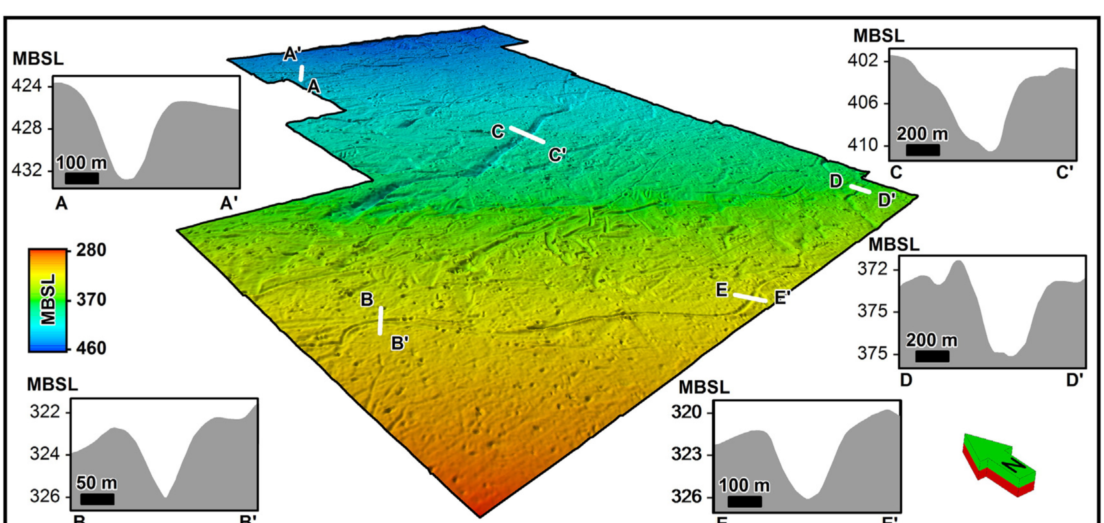

Fig. 3. A 3D perspective image, showing the heavily scoured seafloor with a number of vertical profiles through the iceberg scours. All vertical profiles depths are in metres below sea level.

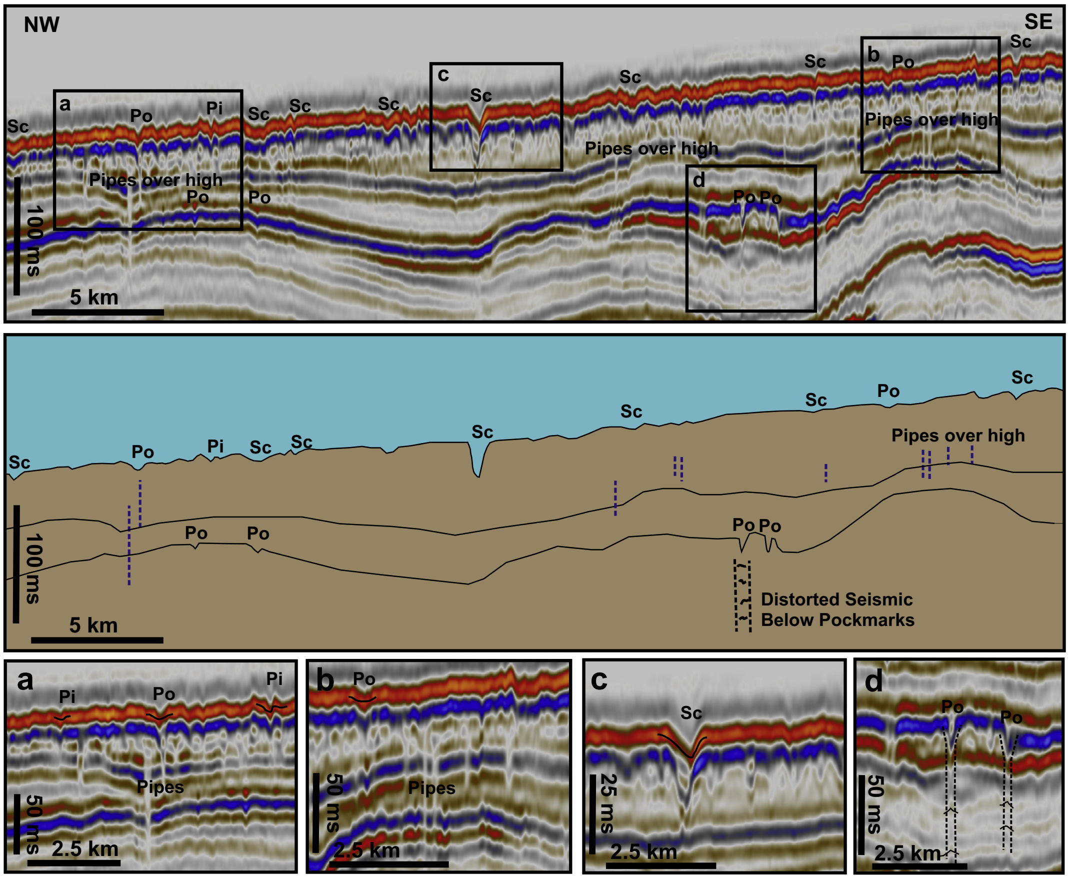

Fig. 4. A regional seismic line from NW – SE of the dataset, showing pits (Pi), pockmarks (Po), scours (Sc) and pipes. For location see Fig. 6. (a) Focuses on pits and pockmarks, showing seismic dimming below the pockmark, (b) Shows pockmarks with distortion of seismic below, (c) Cross-section through the largest scour mark in the survey, (d) Highlights local anticlines and vertical pipe-like structures.

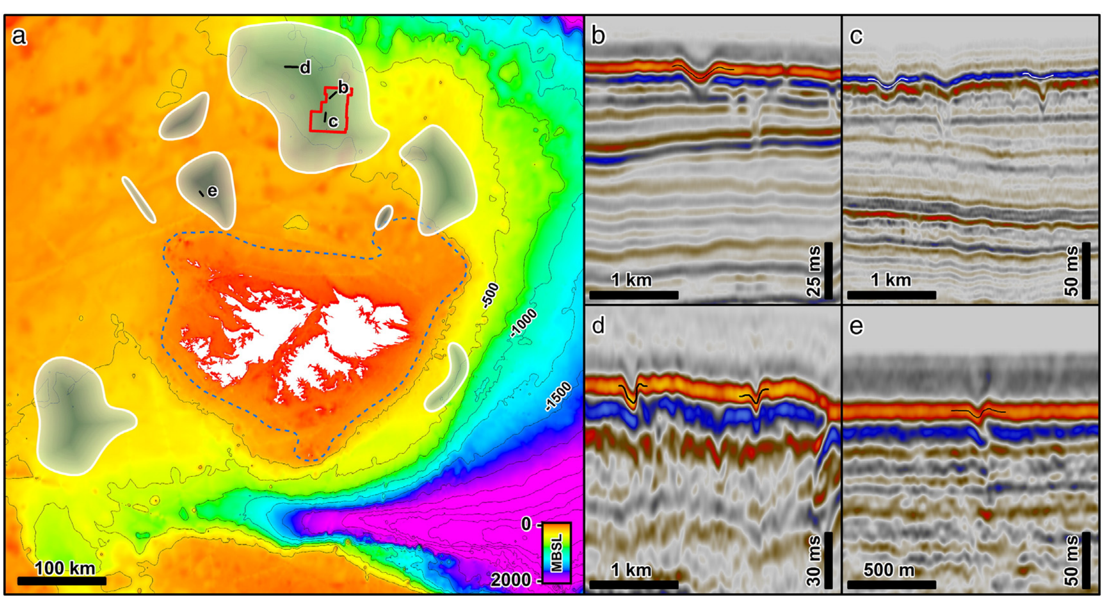

Fig. 5. (a) Shaded polygons show areas offshore the Falkland Islands where 2D seismic reflection data has been used to investigate for additional evidence of iceberg scouring, with depressions identified in all areas - indicative of potential scours, iceberg pits, or pockmarks. For data coverage see Fig. 1 (inset). (b and c) Using the seismic facies and the 3D control provided by the 3D seismic data the acoustic signature of iceberg scouring was determined as v-shaped erosional troughs that are often (but not always) accompanied by one or two berms either side of the trough. The thin black and white lines show examples of iceberg scours identified in the 3D seismic data. (d and e) The 3D seismic facies was used to investigate the 2D seismic data for evidence of iceberg scouring. The black lines show examples of iceberg scouring observed in the 2D seismic data. Locations of panels (b)–(e) shown in (a). Without 3D control on these features their interpretation should be considered as tentative; as indicated by the subtlety of many of the iceberg scours identified on seafloor derived from the 3D seismic data, the acoustic signature is not abundantly apparent even when looking at the subtle scours in a cross-section from the 3D data, and it requires 3D control for the features to be confidently interpreted and distinguished from pockmarks linked with fluid expulsion.

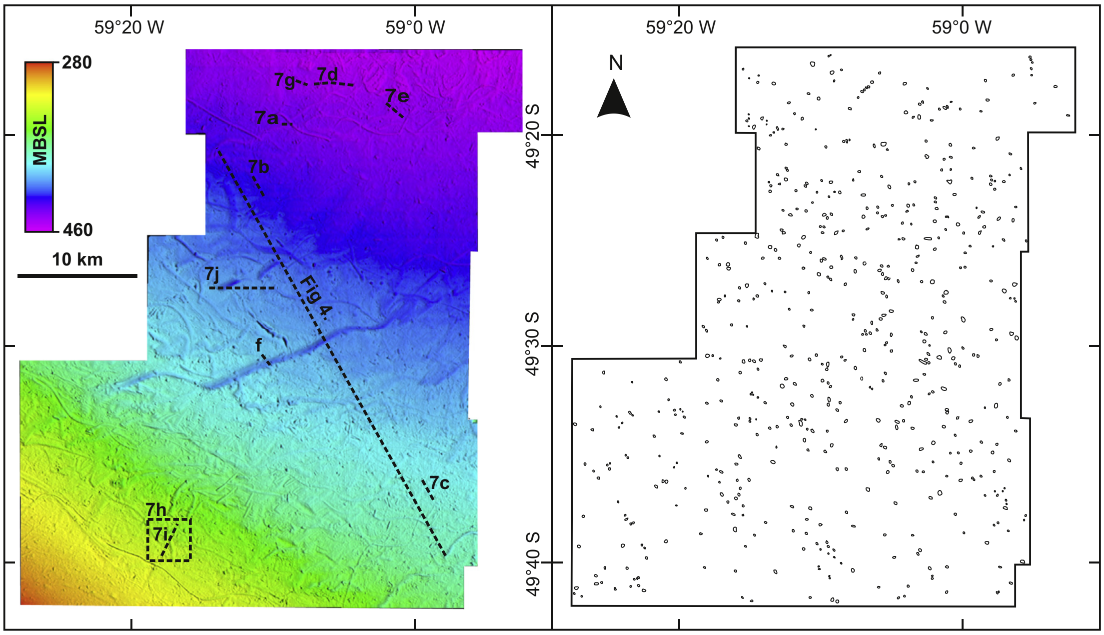

Fig. 6. Map highlighting distributions of pitted features identified on the seabed. 562 pitted features are found evenly distributed across the seabed, reaching up to ~1 km in diameter.

geomorphology, quantity of ice cover at the LGM, and regional ocean currents in the South Atlantic.

Although the majority of the scours are believed to have occurred at or after the LGM, it is possible some scours are records of previous glaciations. Sedimentation rates are assumed to be low during the Pleistocene, which could signify that some seabed scours may have occurred during a prior glacial period. Low sedimentation rates result in minimal interglacial deposits being recorded; therefore, glacial stages cannot be easily separated. The freshness of the features recorded on the seafloor is used to infer that they were formed at or after the LGM with the caveat that an older origin cannot be ruled out.

6.1.1. Glaciation of the Falkland Islands

The record of glacial geomorphology on the Falkland Islands is spatially-limited to the small-scale presence of moraines, cirques, glacially eroded valleys, and tarns (Clapperton, 1971a; Hodgson et al., 2014). The Falkland Islands have extensive, undulating lowlands less than 100 m above sea level (ASL), with few areas elevated above 500 m ASL, and the highest point on the islands being Mount Usborne at 705 m ASL (Wilson et al., 2008). The low-lying landforms and lack of obvious evidence for an extensive ice cover clearly suggests that the Falkland Islands did not have a sufficiently large ice cover to reach the marine setting and calve icebergs large enough to scour depths over ~330 m. Austin et al. (2013) theorised that at the LGM a narrow passage of sea-ice linked the Falkland Islands and Argentina. Regardless of whether the sea-ice cover was perennial or seasonal at the LGM, the presence of such a large cap of sea-ice would have reduced the availability of a significant moisture source with which to seed a large ice cover over the Falkland Islands. As such, the icebergs clearly could not have come from the Falkland Islands and must have come from elsewhere in the South Atlantic.

The sea-ice bridge extension between the Falkland Islands and Argentina is likely to have formed as a result of lower water temperatures during the LGM (Campagna et al., 2007; López-Martínez et al., 2011) and by iceberg accumulation in the area. The freshwater perturbations of meltwater from icebergs would have lowered the density and salinity of ocean water, therefore, creating a cooling effect. As a result, colder local waters surrounding the icebergs would freeze, forming what would have essentially been a graveyard of icebergs and sea-ice. Submarine terraces found along the coast of Argentina tied to low sea-stands are indicative of a lower sea level and sea-ice bridge at the LGM, linking the Falkland Islands and Argentina (Austin et al., 2013). The documentation of iceberg scours in the NFB, and likely iceberg graveyard, could suggest cooling of seawater in the area enhanced the development of the sea-ice cover. The presence of a sea-ice bridge has further oceanographic implications; the icebergs scouring the NFB would have been transported via the East of the Falkland Islands.

6.1.2. Glaciation of South Georgia

South Georgia is a sub–Antarctic island situated in the South Atlantic. Contemporary ice fields are identified in the centre of the island and several studies suggest that an ice sheet covered the island at the LGM (Clapperton, 1971b, 1990; Bentley et al., 2007; Graham et al., 2008). Two models have been established on South Georgia for a restricted or an extensive ice cover at the LGM. The restricted model suggests that at the LGM, ice was limited to the inner fjords and this is supported by radiocarbon dating of lacustrine deposits (Bentley et al., 2007). These deposits suggest that no ice was present at 18.6 ka on the surrounding shelves, although this does not preclude a more extensive ice cover prior to this. The extensive model suggests that the LGM ice cover extended onto the continental shelf of South Georgia (Bentley et al., 2007; Graham et al., 2008). Dating evidence for the glacial features on the shelf is lacking, however, if the restricted model is correct then it remains uncertain as to when and how the glacial features on the shelf were formed.

On the continental shelf, Graham et al. (2008) identified over ten troughs, with seven in a northward orientation in water depths of 250 m to 380 m. These troughs are thought to relate to the extension of ice on to the continental shelf at some stage during the Pleistocene. If these troughs were occupied by ice at the LGM, the maximum water depths seen in the troughs could suggest that the islands were capable of producing icebergs at the LGM or earlier glacial periods. However, even if the model for an extensive ice cover at the LGM is correct, South Georgia seems an unlikely source of icebergs to the NW Falkland Plateau due to the LGM ocean current patterns. McCave et al. (2014) suggested that glacial speeds were slower at the LGM, but that the ACC changed little between the LGM and Holocene. If the ACC has not changed, then present directions indicate the ACC is flowing away from the Falkland Islands.

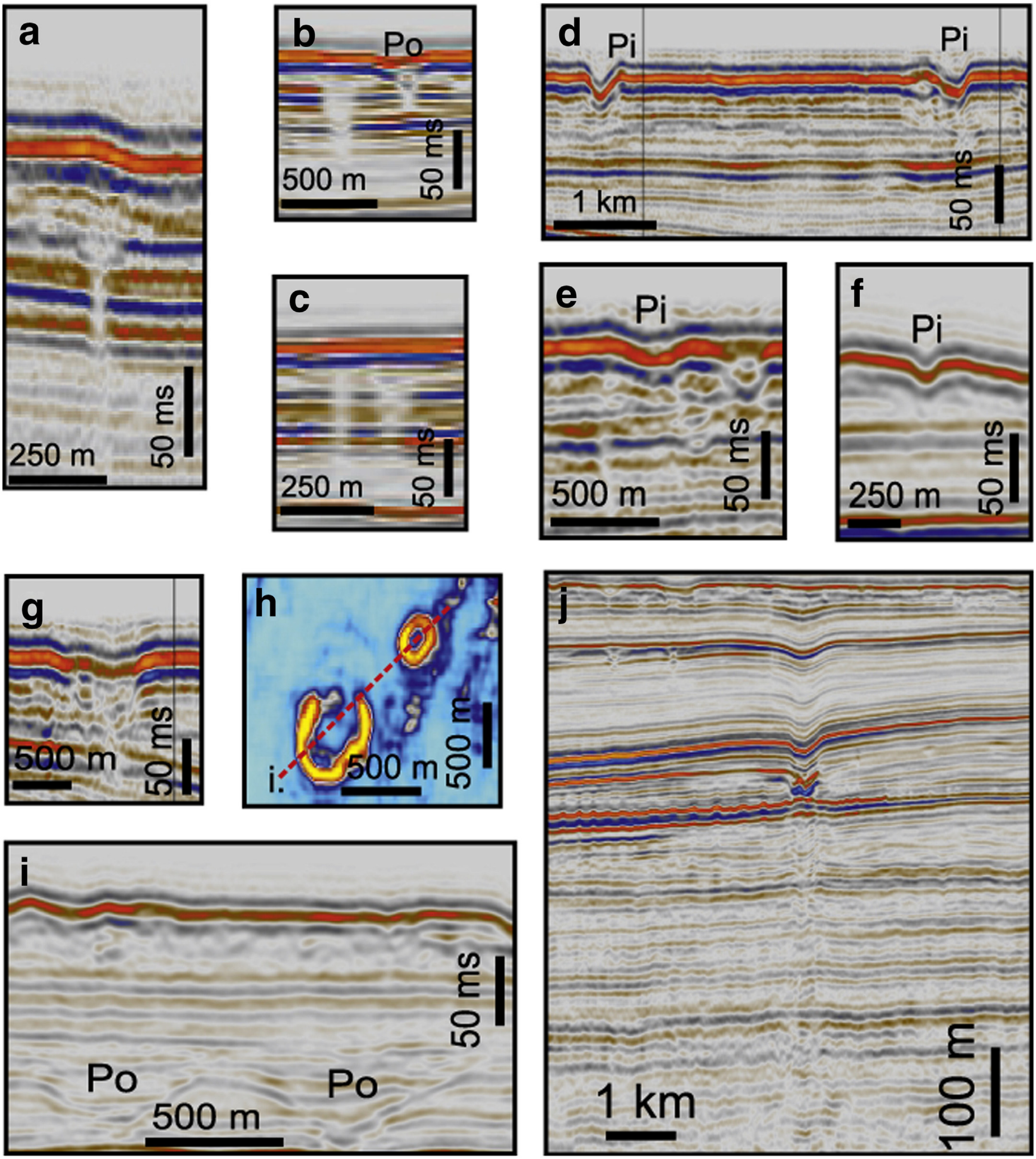

Fig. 7. (a)–(c) Shallow pipes within the subsurface are identified from the local dimming of amplitude in a vertical orientation. Sometimes the pipes are connected to a pockmark (Po). (d)–(f) Iceberg pits (Pi) are identified from their asymmetry and location. They are almost always found on the seafloor. (g) A single pockmark located on the seafloor, with associated dimming below. (h) RMS amplitude time-slice of (i), which shows palaeo - pockmarks located ~150 ms below the seafloor. (j) Stacked pockmarks and potential deep roots up to 700 m below sea level. For localities see Fig. 6.

Additionally, contourites in the Scotia Sea (Howe et al., 1997; López-Martínez et al., 2011) and the Falkland Trough (Koenitz et al., 2008) suggest an eastward drift during inter-glacial and full-glacial periods, taking any icebergs calved from South Georgia away from the Falkland Islands. The water depths measured in the South Georgia troughs would also be considerably shallower, by ~100 m, compared to the LGM water depths where the iceberg scours are located in the NFB. Thus, even if the ice cover was extensive enough to be marine-terminating, any icebergs that were calved were unlikely to have been sufficiently large enough to preserve enough of its mass whilst crossing

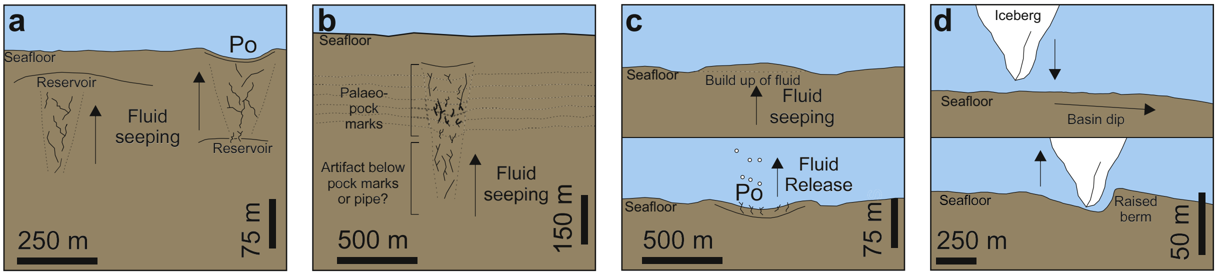

Fig. 8. Summary schematic representing seafloor shaping mechanisms related to iceberg scour and fluid expulsion. (a) Schematic of fluid seeping upwards through a series of fractures in clay rich strata. Fractures form when fluid exceeds a critical pressure to escape the underlying shallow aquifer/reservoir. (b) A series of stacked pockmarks represent continued fluid build-up and release. Stacked pockmarks do not reach the seafloor, which suggests fluid supply has ceased in recent years. (c) Pockmark highlighting the fluid build-up below the seabed and release of fluid. (d) Diagram of a pit being formed by an iceberg. The iceberg drops vertically downward in the water column and the asymmetry of the pit depends on the deepening direction of the basin and direction of the iceberg.

the South Atlantic, particularly given that the ocean currents at the LGM were thought to be slower (McCave et al., 2014).

6.1.3. Glaciation of Patagonia

The Patagonian Ice Cap is found along the Andes Mountain Chain, and the Southern Patagonian Ice Field in Chile and Argentina covers an area of 13,000 km^2 (Geological Survey, 1998). Currently glaciation is restricted between latitudes of 45 to 55° S, whereas the full extent of ice at the LGM is thought to have extended north and south between 35 and 57° S, and to have been marine-terminating in the west (McCulloch et al., 2000). After the LGM, McCulloch et al. (2000) suggested a series of three warming events began the ablation of the Patagonian ice cover, starting with the onset of deglaciation (~17 ka), followed by a warming in the North Chilean Lake District at ~15.5 ka and then toward the Southern Patagonian Ice Field at ~11 ka. All of the Patagonian Ice Sheet in the east was grounded above sea level, and thus could not provide the potential source of the icebergs that scoured in the NFB. In the west, however, much of the western margin of the ice sheet is thought to have been marine-terminating at the LGM (Caniupán et al., 2011; Darvill et al., 2016), albeit in particularly shallow waters after the coeval drop in sea level is considered. Although the direction of the ACC and western branch of Falkland/Malvinas Current at the LGM (Nowlin and Klinck, 1986) lends itself well to icebergs being sourced from the Patagonian Ice Sheet, the shallow water depths (Muñoz et al., 2013) into which any icebergs would have been calved, and limited extent of marine-terminating ice (Clapperton, 1990; López-Martínez et al., 2011), would have placed a serious restriction on icebergs of sufficient size reaching the NFB.

6.1.4. Glaciation of the Antarctic Peninsula

The Antarctic Peninsula is the largest ice mass in proximity to the Falkland Islands and would have had the most significant ice sheet extent at the LGM. At the LGM the Antarctic grounding line extended to the edge of the continental shelf (Anderson et al., 2002), with the maximum ice sheet volumes being achieved at different places around the margin (Huybrechts, 2002; Bentley et al., 2014; Maris et al., 2014). Modern ice cover on the Antarctic Peninsula currently averages ~500 m thick, flowing east and west (Denton et al., 1991; Heroy and Anderson, 2005). Glacial cross-shelf troughs and submarine glacial geomorphology indicate that the Antarctic Peninsula Ice Sheet was either grounded on the continental shelf or present as ice shelves at the LGM (Heroy and Anderson, 2005). The size of the ice cover over the Antarctica Peninsula at the LGM means that it could have easily calved icebergs of sufficient draft to scour water depths of ~330 m in the NFB. The trajectory of the ACC means that icebergs could have travelled from the Antarctic Peninsula and have entered the East Falkland/Malvinas Current and travelled into the NFB.

The ACC links all the major oceans on Earth and is driven by westerly winds (Orsi et al., 1995), whilst the Falkland/Malvinas Current is a northern extension of the ACC that helps to bring cooler freshwater to the mid-latitudes of the South Atlantic (Garzoli, 1993) (Fig. 1). This finding has significance because there appears to be little other explanation for how icebergs could have scoured in the NFB. The shallow water depths of the Falkland Plateau and sea-ice cover between the Falkland Islands and South America during the last glacial cycle mean that the icebergs could only have come from the east of the islands (López-Martínez et al., 2011).

The icebergs were most likely calved from the marine-terminating ice cover in either the Amundsen Sea or Bellingshausen Sea, or indeed both. The LGM ice cover terminating in the Weddell Sea is unlikely to have been the source for the icebergs because of the prevailing currents taking icebergs away from the South Atlantic (Fig. 1) (López-Martínez et al., 2011).

The transit time of an iceberg, from calving to seafloor scouring, can be predicted assuming present day ocean current velocities. At the LGM, if the ACC had a similar pattern to that of today, then surface velocities may have been between ~10–65 cm s^{-1} (Nowlin and Klinck, 1986; Rintoul and Bullister, 1999; Zambianchi et al., 1999; Thorpe et al., 2002; Cunningham et al., 2003). Therefore, icebergs responsible for scouring in the NFB would have travelled ~2000 km, from the Amundsen Sea to NFB, in ~35–230 days.

Considerations of glacial history and likely ice sheet geometries also suggest that the western side of the Antarctic Peninsula was the most likely source of the icebergs. The prevalence of so many deep-draft icebergs in a relatively small area in the NFB has a possible glacio-dynamic implication. Although the summer sea-ice extent at the LGM is poorly constrained, the winter sea-ice extent (Fig. 1) extends sufficiently far north that it almost closes the Drake Passage. As such, even with summer sea-ice melt, it is difficult to envisage how icebergs could penetrate through an expansive sea-ice cover in such large numbers before being entrained into the northward flowing East Falkland/Malvinas Current. It would appear more likely that the icebergs were calved during a period when sea-ice conditions had significantly ameliorated and provided less of a barrier to iceberg flow northwards during the deglaciation after the LGM.

In order for icebergs to scour the seafloor in the NFB, the icebergs, if sourced from the Antarctic Peninsula, must have been of significant size to survive travelling ~2000 km. During deglacial conditions it is possible that one of the fringing ice shelves on the Antarctic Peninsula might have collapsed or an ice stream uncoupled from its bed and underwent rapid retreat. Under such a scenario, an ice shelf collapse or ice stream retreat might have provided a sufficient number of deep-draft icebergs to send an iceberg armada into the ACC. Reduced sea-ice conditions would have then allowed the icebergs to travel northward through the ACC before becoming entrained into East Falkland/Malvinas Current taking them into the NFB. If this scenario is correct it has some interesting implications for the palaeo-oceanography either at the LGM or during the subsequent retreat of ice from the continental shelves of the

Antarctic Peninsula. The record of iceberg scouring suggests that the East Falkland/Malvinas Current was active at the LGM or during the deglaciation, and that the oceanography around the Falkland Islands, and more broadly the South Atlantic, was similar to the present, with the ACC providing the dominant control on weather patterns and ocean circulation around Antarctica.

6.2. Significance of pockmarks and iceberg pits in the North Falkland Basin

6.2.1. Potential sources of pockmarks

Pockmarks form when fluid is expelled from sediment, either during de-gassing or de-watering of sediment, or when petroleum migrates upward from active hydrocarbons. In the NFB, it is well known that multiple source rock intervals exist, with the post-rift phase being dominated by organic, lacustrine rocks, intercalated with coarse-deltaic clastics (Bunt, 2015; Farrimond et al., 2015; Williams, 2015). Fluid could be supplied to the seabed from faults acting as conduits, or through gradual diffusive seepage upwards. Sources with total organic carbon (TOC) of 2–12 (%) are recorded from ~1550 to 2350 m total vertical depth (TVD) in wells targeting the Sea Lion complex (local prospect) (Farrimond et al., 2015). The Sea Lion complex is located directly below the study area and it seems plausible that hydrocarbon seepage could be responsible for some of the pockmarks, particularly those that show pipe-like features or sub-vertical stacked relationships (Figs. 4d and 7j).

De-gassing of the overburden may also be responsible for sourcing of pockmarks. Methane may be generated near the seafloor during the shallow burial of organic rich sediments (Hovland and Judd, 1988; Andresen et al., 2008). Tertiary sediments (upper 400 m below the seabed) in the basin are dominated by intervals of sandstone and claystones, intercalated with siliceous oozes composed of planktonic and benthic organisms (Richards and Hillier, 2000; MacAulay, 2015). With time, biogenic gas is likely to be expelled into interstitial pore space. When the interstitial pore pressure exceeds the fracture gradient of the overlying sediments, the gas is discharged and pockmarks may form if fluid flow is rapid at the sediment-water interface (Kelley et al., 1994). Pockmarks at the seabed are often identifiable from the distorted seismic underneath, or pipe-like structures reducing the amplitude directly below the pockmark. This could indicate gas in the sediment, concealing reflectors (Schubel, 1974), or churning or fracturing of sediment within the sub-vertical conduit (Cartwright et al., 2007).

De-watering of sediment could also be responsible for pockmark creation if the composition of siliceous oozes does not retain adequate organic matter to expel biogenic gas. Clays retain a high porosity when deposited, which then reduces exponentially during burial, reducing up to 40% in the first 500 m (Velde, 1996; Judd and Hovland, 2007; Long et al., 2011; Hartwig et al., 2012). The clay-rich overburden pore space would consist largely of water upon early burial, which would be subsequently discharged by slow diffuse migration, or rapid episodic flow (Velde, 1996; Hartwig et al., 2012).

It is possible that the release of pore fluid from pockmarks at the current seafloor is related to glacial processes. Pockmarks can often be observed around the world in areas where iceberg scours have been identified (e.g. Winsborrow et al., 2016), with some authors relating erosive glacial landforms to a reduction in overburden pressure facilitating shallow subsurface seal breaching, fluid flow and pockmark formation (Harrington, 1985; Fader, 1991). The impact of an iceberg hitting the seafloor is likely to alter stresses within the sediments, potentially even creating fractures within the subsurface, proximal to the seabed. Icebergs in the NFB have incised the seafloor across the entirety of the study area, reducing shear strength in the locality of the scour, thus facilitating the degassing of sediments. Although the scouring of icebergs may account for pockmarks on the present seabed, it does not account for pockmarks that formed on palaeo-seafloors. Below the present seafloor iceberg scours and pits are not identified, meaning another mechanism must be responsible if pockmarks are related to an instantaneous event.

Pockmarks may be related to periods of sea-level falls (Lafuerza et al., 2009; Plaza-Faverola et al., 2011), when the hydrostatic pressure is reduced. This could result in the interstitial pore pressure exceeding that needed to expel gas in sediments of low compressibility (Hermanrud et al., 2013). As hydrostatic pressure decreases, so does the solubility of gas, resulting in over-pressuring of sediments and gas expulsion at the seafloor (Lafuerza et al., 2009; Plaza-Faverola et al., 2011; Hermanrud et al., 2013). If this is the case then continuous reflections with higher densities of pockmarks would be likely related to low sea-levels. Although, the presence of gas enhances the potency of this mechanism pockmarks can also form without gas being present in the sediments (Hermanrud et al., 2013). In the absence of a trigger it is also possible that pockmarks are not related to an instantaneous event, and could be related to the supply of fluid alone, but in these cases a subsurface fluid focus point should be identifiable and pockmark distribution more localised.

6.2.2. Palaeo-pockmarks

Pockmarks in the area are found from the present seafloor through to ~300 m below the seabed. Buried pockmarks, which are believed to have formed as seafloor features, indicate periods of non-deposition (Hovland et al., 1984). Stacked pockmarks (Fig. 7j) indicate that focused fluid flow happened repeatedly throughout the Cenozoic, up to ~700 m below sea level. It is unknown whether these formed due to compaction and pore-water escape or gas, or a combination of both. The presence of multiple pockmarks, pits, and scours on the present seafloor suggests that the seafloor geomorphology has been largely unchanged since the LGM or deglaciation.

7. Conclusions

Iceberg scours identified in the NFB are believed to have been sourced from the Antarctic Peninsula at the LGM or during early deglaciation. This is further evidence that giant icebergs, scouring in water depths greater than 330 m can travel north of 50° S. The icebergs were likely calved in the Bellingshausen or Amundsen Seas and travelled over ~2000 km north, through the ACC and into the South Atlantic. Here, they were transported northwards and finally westwards into the NFB by the Falkland/Malvinas Current. This scouring record suggests two things; (1) that the East Falkland/Malvinas Current was in operation during the last glacial cycle, carrying icebergs and cold Antarctic-derived fresh waters into the South Atlantic, and (2) that in order for the icebergs to traverse such a large distance and still be able to scour in water depths of over ~330 m the icebergs must have originally been very large when they were calved. Potentially, the large number of comparatively deep-draft icebergs at this latitude may reflect the disintegration of a marine-terminating ice mass on the Antarctic Peninsula. These findings are further evidence of iceberg sourcing from the Antarctic Peninsula and transportation to high latitudes, in line with the findings of López-Martínez et al. (2011).

Observations of iceberg scours west of the Falkland Islands suggest that the accumulation of icebergs could have resulted in an iceberg graveyard to the southwest of the NFB. This may have contributed to the formation of a sea-ice bridge, by freshening and cooling the surrounding waters. In addition, the large presence of ice in the area would reduce moisture availability and hinder the ability to seed local ice cover over the Falkland Islands.

The main seabed relief generator at present is the product of fluid escape on the seafloor, and resulting pockmarks. Iceberg scours are common in the basin; however, icebergs are not expected to be an issue for petroleum related seabed installations as they were likely formed several thousands of years ago during glacial conditions. Iceberg occurrence in the surrounding waters of the Falkland Islands is still possible, with a few mega icebergs from Antarctica tracked to just north of the Falklands between 1979 and 2003 (Silva et al., 2006); although it is unlikely that the consequences of such mega icebergs could not be mitigated against.

Despite their morphological similarities, iceberg pits and pockmarks have been distinguished by their relation to fluid flow features, location, symmetry, shape, diameter, and seismic character. This has allowed us to use the seismic data to identify pipes that reach depths of 300 m below the seafloor. Focused fluid flow was intermittent in this area, reflecting either shallow sediment de-gassing, de-watering or deeper petroleum systems activity, or a combination of all mechanisms. The observations and analyses presented would benefit from further seafloor sediment sampling of scours, pits, and pockmarks to help constrain timing of bedform generation and the fluids involved in pockmark formation.

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